# C-A D Engineering Design Support Documentation Cover Page

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|---|---|
| Title: ***C3Inflector Thermal-Stress Analysis2 (2nd analysis)*** | Author: V. Badea and S. Bellavia |
| Subject: Thermally induced stress state of the C3 inflector septum upon incident beam | |
| C-A Department Group: Mechanical | Approval: J. Tuozzolo |
| Documentation Type:<br>Written Technical Paper<br>**X** Design Calculations<br>Design Review Presentation<br>Design Certification<br>Specification<br>Procurement Documentation<br>Safety/ALARA Review Presentation<br><br>Other:___________________________ | Equipment Type:<br>Magnets and Power Supplies<br>Vacuum Systems<br>RF Systems<br>Cryogenic Systems<br>Experimental Equipment<br>Beam Instrumentation<br>Water Systems<br>Buildings, Structures, and Shielding<br><br>**X** Other: Inflector___________________ |
| Equipment Location:<br>Tandem Van DeGraff<br>Linac<br>**X** Booster<br>AGS<br>RHIC<br>912 Experimental Area<br>919 Experimental Area<br>RHIC Experimental Areas<br>____________________________________<br>Buildings, Structures, and Shielding<br>Other<br><br>____________________________________ | Associated information for cataloging (if available fill in the number):<br>C-A D Design Room Job No.<br><br>____________________________________<br>**X** C-A D Design Room Drawing No.<br><br>_D36-M-2256-5__________________________<br>C-A D Specification No.<br><br>____________________________________<br>C-A D Experiment No.<br><br>____________________________________<br>Other<br><br>____________________________________ |

Discussion:

Additional analysis was performed for beam incident upon the Booster C3 Inflector Septum, as requested at a meeting held on March 4th,2004. (see previous document). This additional analysis addresses the following three items:

1. A longer run time (3600 sec vs. the previous 900 sec analysis)
2. The effect of radiation heat transfer
3. The effect of varying thermal contact on the edges of the septum.

Parameters:

Same material as previous analysis.

Assumptions:

- Emissivity of material = .1

Radiation Heat Transfer Hand Calculations (See appendices, attached):

- Although some temperature reduction occurs by 900 seconds, calculations indicated that the material approaches equilibrium via radiation heat transfer by 3600 seconds.
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FEA Model:

- In order to be able to run longer run times as well as include radiation, it was necessary to investigate the possibility of using more pulses per calculation sub-step or even a continuous heat load. After looking at the effect of combining 1 pulse into 5, and then into 10, it was noticed that there was little change in the transient response and resulting temperature profile. A continuous equivalent heat load of 28 Watts (100 Joules/3.6 seconds) was then applied showing little effect on the transient thermal response and temperature profile, so this was used for all the following calculations.
- To further reduce calculation run-time, the model was re-meshed, retaining the fineness needed in the area of interest, but with a gradually decreasing element size as distance from this area increased.

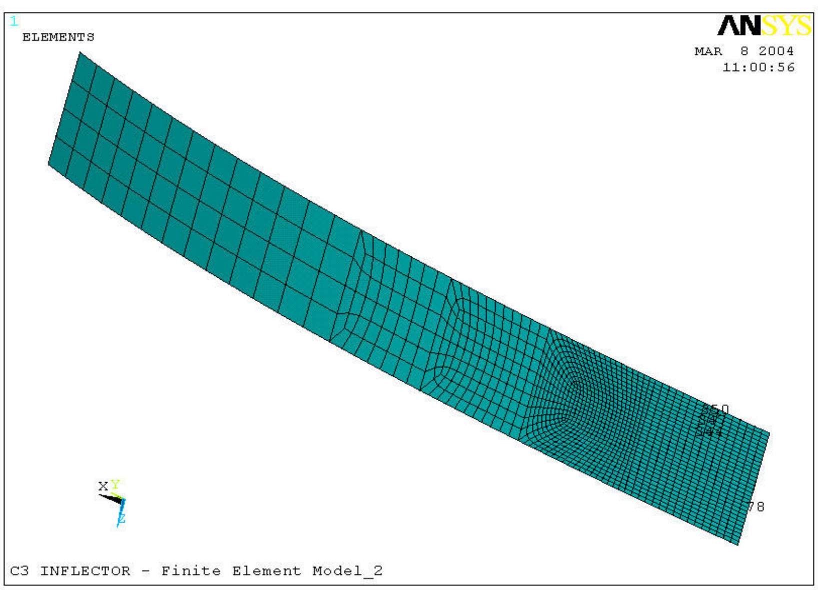
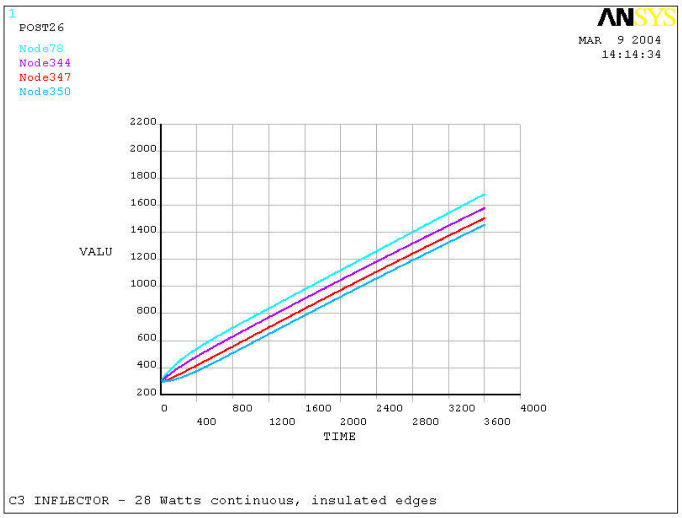



Figure 1. Improved Element Distribution for FEA models.

## Analysis Method & Results:

The following cases were analyzed:

1. No conduction to edges (insulated) and no radiation
2. Radiation Only
3. Perfect-contact conduction to edges at 298K, no radiation
4. Perfect-contact conduction to edges at 298K, with radiation
5. Typical contact conduction to edges at 298K, no radiation
6. Typical contact conduction to edges at 298K, with radiation



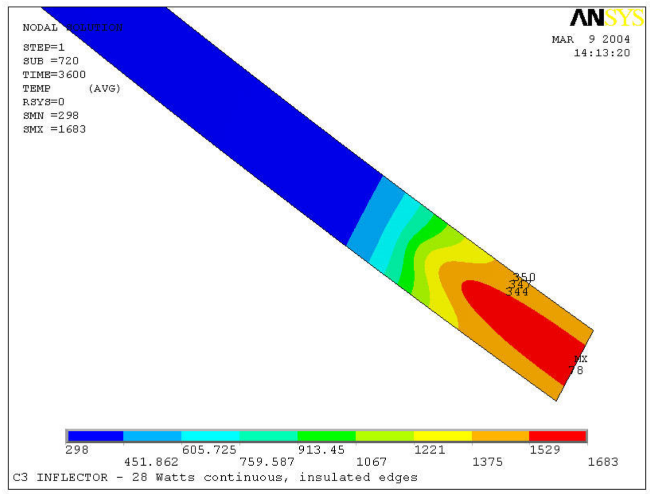
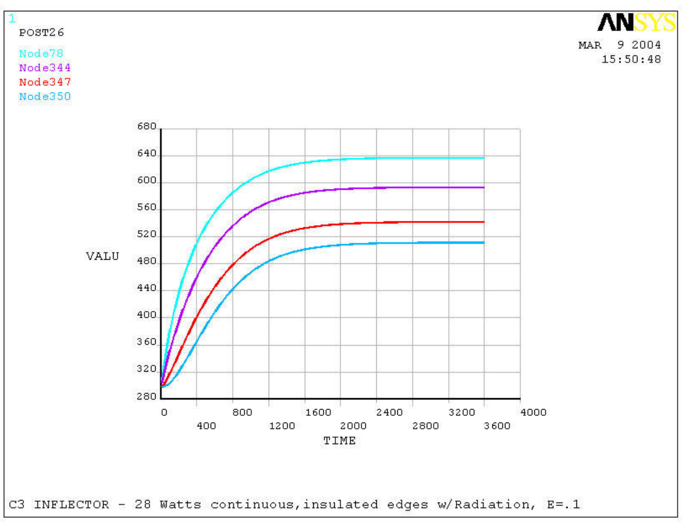




Figure2-1: Transient response & temperature profile for insulated edges, no radiation.



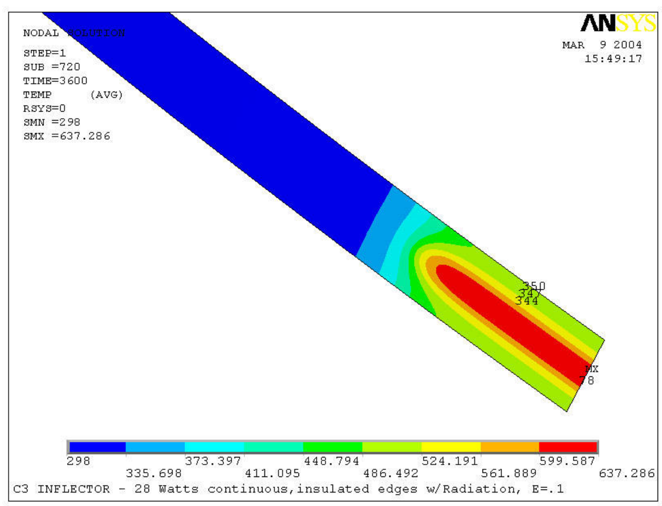




Figure 2-2. Transient response & temperature profile for radiation only.

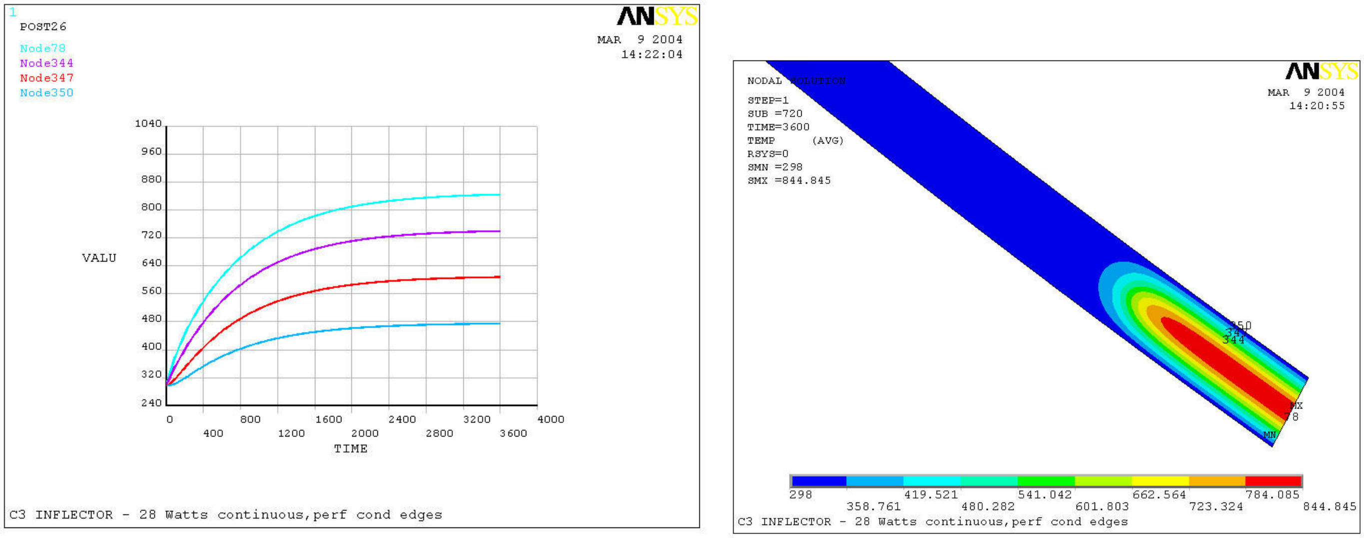



Figure 2-3. Transient response & temperature profile for perfect-contact conduction only

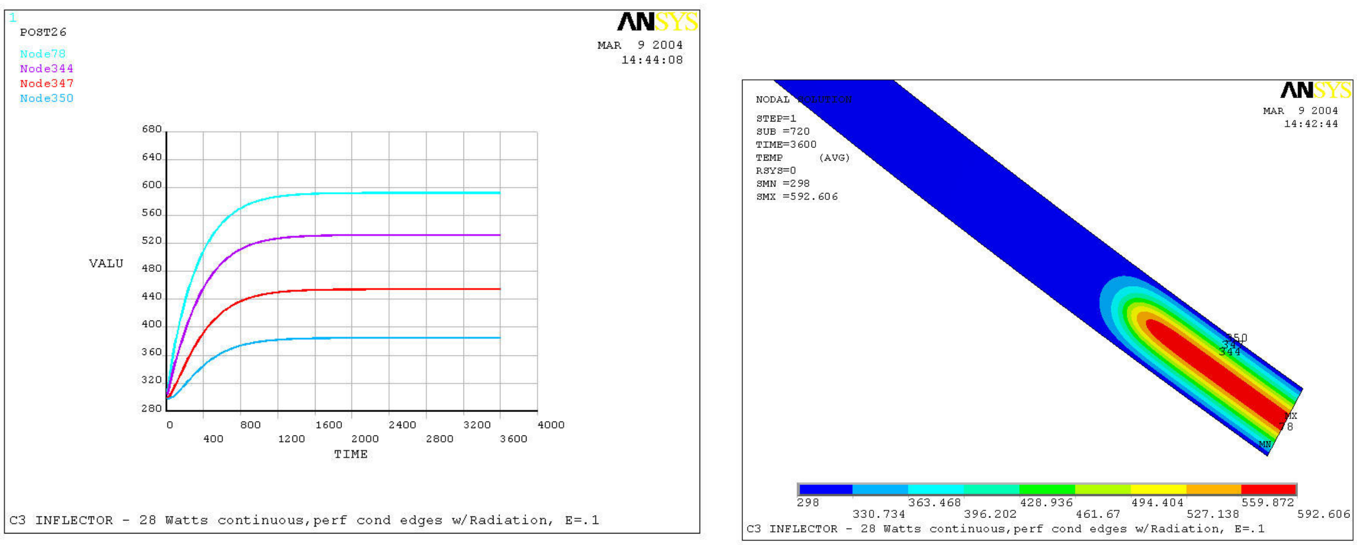



Figure 2-4. Transient response & temperature profile for perfect-contact conduction w/radiation.

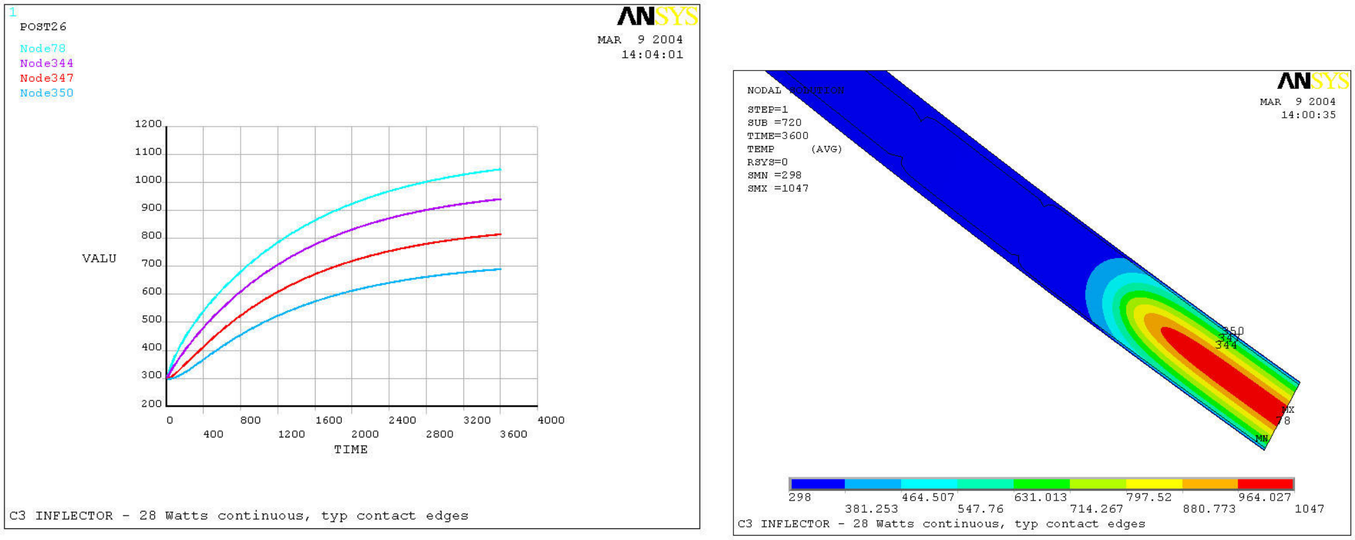



Figure 2-5. Transient response & temperature profile for typical contact conduction, no radiation.

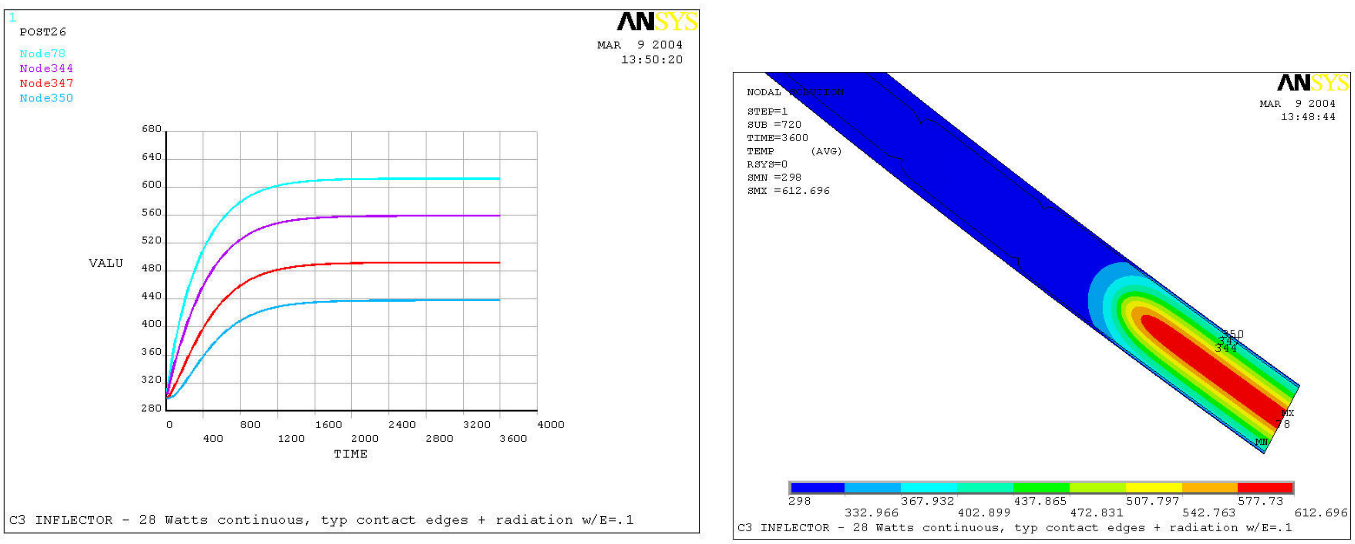



Figure 2-6. Transient response & temperature profile for typical contact conduction, with radiation.

As can be seen in the above figures, the effects of better thermal contact and radiation are more prominent as time progresses. However the effects around 900 seconds, where the previous analysis was performed, are not that significant. It is believed that case 6 - typical contact with radiation - is the most representative of the actual system. This was then used to perform the deflection and stress analysis.

The following graph shows the progression of temperature, deformation and stress as a function of time. (note, these are linear static results, and do not include effects of buckling).

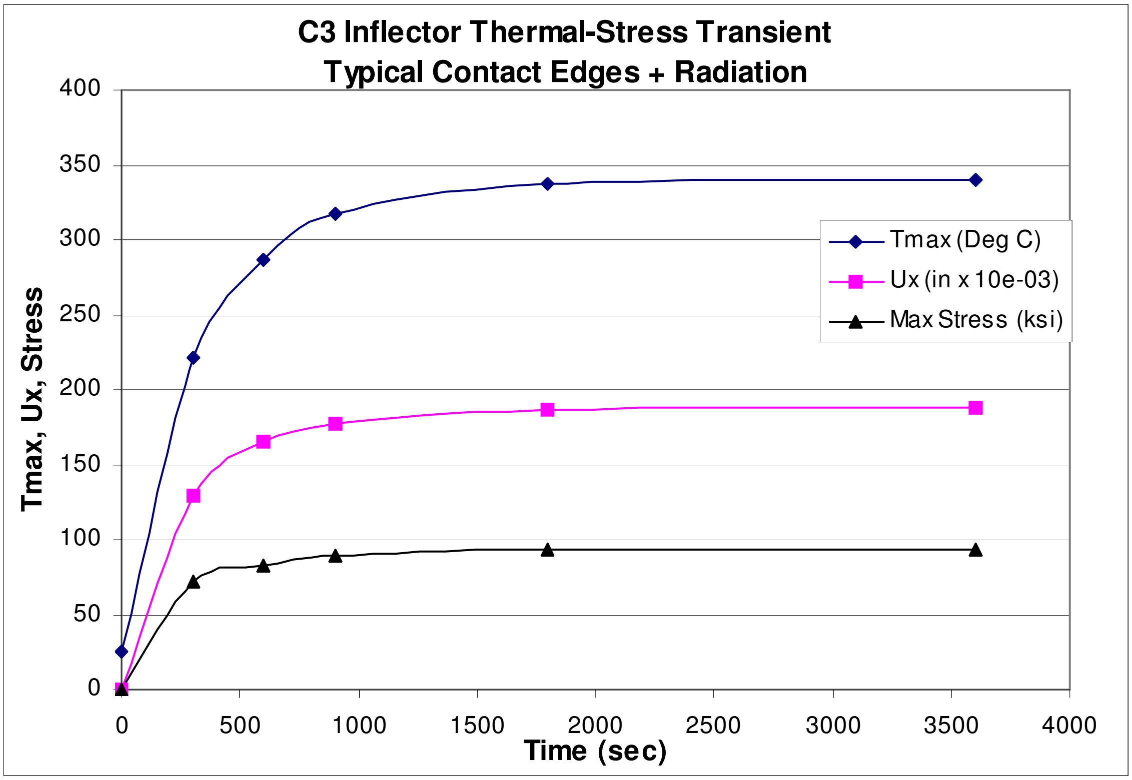



Figure 3. Temperature, Deflection and Stress transient.

Note that after 900 seconds, all parameters of interest are rapidly reaching equilibrium.

Additional analysis was performed including the effects of buckling. Results indicate a peak stress of 132ksi, which is approximately 6 ksi above the yield limit of this material:

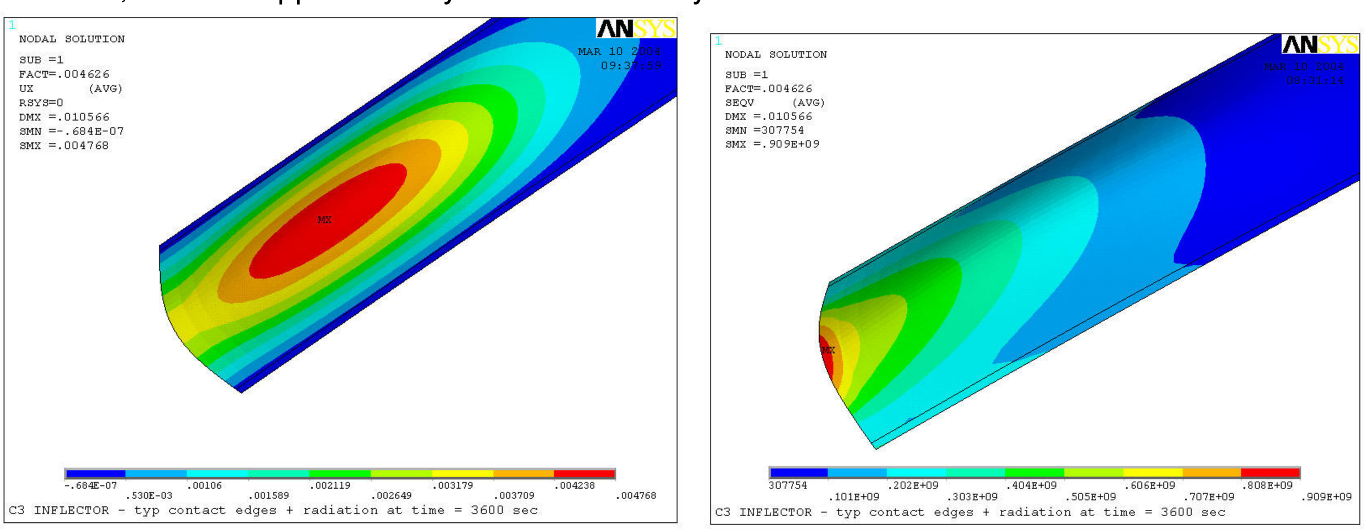



Figure 4. Deflection and Stress with buckling.

## Summary / Conclusion:

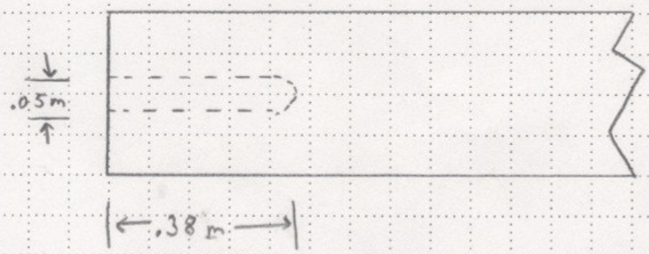
Thermal contact with the edges of the support structure as well as radiation heat transfer will limit the peak temperature of the inflector septum from “running away” and could be at or below 400 deg Celsius.

It is still believed that yield failure in the local area of the heat load can occur shortly after 900 seconds of incident beam, where peak temperatures approach 400 deg C locally with a large temperature gradient across the width of the septum.

As stated in the previous analysis, It is recommended to limit beam upon the C3 Inflector Septum to 15 minutes or less.

# ENGINEERING ANALYSIS

| MODEL | SUBJECT C3 INFLECTOR RADIATION HEAT X-FER | | INDEX |
|---|---|---|---|
| ANALYST S. BELLAVIA | CHECKER | DATE 3/5/04 | PAGE 1 OF 1 |




Assume small area (.05m x .38m) radiates to space : (x2 for both sides)

$$q = A F \varepsilon \sigma (T^4 - T_\infty^4)$$

assume emissivity, $\varepsilon = .1$

$F = 1.0$

Let $T_{avg} \approx (635k + 597k)/2 = 616k$ (343°C)

$T_\infty = 298\ k$

stefan-boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ W/m^2\text{-}k^4$

$A = .05m \times .38m = .019\ m^2$

$\therefore$

$$q = 2 \times (.019\ m^2)(1.0)(.1)\left(5.67 \times 10^{-8} \frac{W}{m^2\text{-}k^4}\right)(616^4 k - 298^4 k)$$

$\boxed{q = 29.3\ \text{watts}}$ or Joule/sec

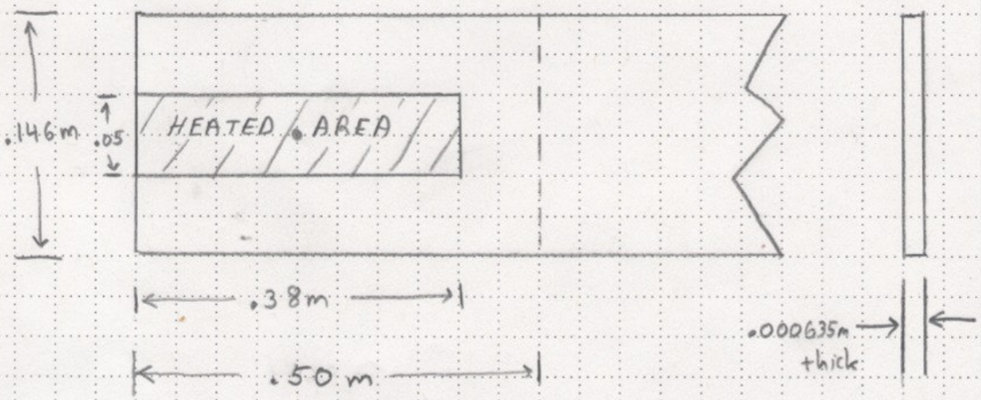
Note: Average Power in $= \dfrac{100\ \text{Joules}}{3.6\ \text{sec}} = 27.8$ watts

This occurs when T = 718 k (445°C),

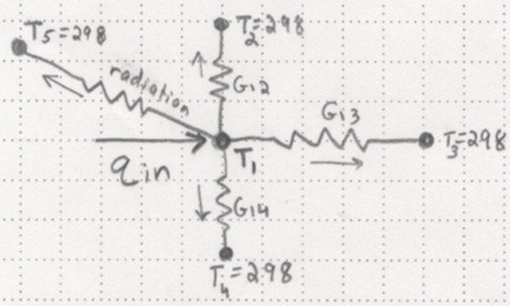
it is in thermal equilibrium

# ENGINEERING ANALYSIS

| MODEL | SUBJECT C3 Inflector Transient Thermal Response w/Radiation | | INDEX |
|---|---|---|---|
| ANALYST S. BELLAVIA | CHECKER | DATE 3/6/04 | PAGE 1 OF 3 |




If assume Heated Area can be represented as a single Node at center, Thermal Network is as follows:




Can do Transient as a series of quasi-steady-state steps:
(as long as $\Delta t \ll \tau$ (time constant of system))

$\therefore$ q in = q out at each step:

$$q_{in} = \underbrace{\frac{(T_{i+1} - T_i)\, m C_p}{\Delta t}}_{\text{Heat Capacitance}} + \underbrace{(T_i - 298)(G_{12} + G_{13} + G_{14})}_{\text{Conduction}} + \underbrace{\sigma F A \epsilon (T_i^4 - 298^4)}_{\text{Radiation}}$$

# ENGINEERING ANALYSIS

| MODEL | SUBJECT | | INDEX |
|---|---|---|---|
| ANALYST | CHECKER | DATE | PAGE 2 OF 3 |

Solving for $T_{i+1} = f(\text{time})$

$$T_{i+1} = T_i + \frac{\Delta \tau}{m\,C_p}\left\{ q_{in} - (T_i - 298)(G_{12} + G_{13} + G_{14}) - \sigma F A \epsilon \left(T_i^4 - 298^4\right) \right\}$$

(Note, this is average "bulk" temperature, NOT the Peak temp)

Assumptions + Constants:

1. Heat Capacitance is for entire area of interest
2. Radiation only transmitted from heated area, $F = 1.0$, $\epsilon = 0.1$

$q_{in} = 100\ \text{J} / 3.6\ \text{sec} \approx 28\ \text{watts}$

For Ti-6AL-4V : $k = 6.7\ \text{w/m-k}$ ; $C_p = .54\ \text{kJ/kg-k}$ ; $\rho = 4430\ \text{kg/m}^3$

Capacitance:

$$m C_p = (\rho \times \tau \times w \times L)\, C_p = (4430)(.000635 \times .146 \times .5)\, C_p$$

$$= (.205\ \text{kg})(.54\ \text{kJ/kg-k}) = .111\ \text{kJ/k} = 111\ \text{J/k}$$

Conduction:

$$G_{12} = G_{14} = \frac{kA}{x} = \frac{(6.7\ \text{w/m-k})(.000635 \times .38)}{(.048\ \text{m})} = .0337\ \text{w/k}$$

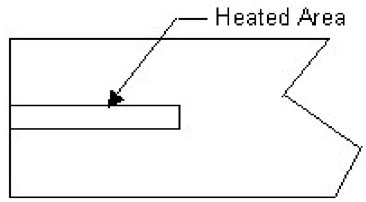
$$G_{13} = \; = \frac{(6.7\qquad)(.000635 \times .05)}{(.5 - .38)} = .0018\ \text{w/k}$$

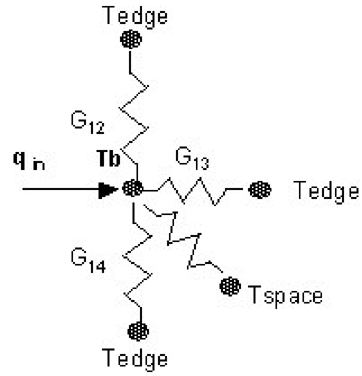
Radiation:

$$\sigma F A \epsilon = \left(5.67 \times 10^{-8}\ \frac{\text{w}}{\text{m}^2 \cdot \text{k}^4}\right)(1.0)(2 \times .05 \times .38)(.1) = 2.15 \times 10^{-10}\ \frac{\text{w}}{\text{k}^4}$$

SEE SPREADSHEET(s) ATTACHED

| | | |
|---|---|---|
| mCp | 111 | J/K |
| $G_{12}$ | 0.0337 | W/K |
| $G_{13}$ | 0.0018 | W/K |
| $G_{14}$ | 0.0337 | W/K |
| $\sigma FA\varepsilon$ | 2.15E-10 | W/k⁴ |
| $q_{in} =$ | 28 | Watts |
| $T_{edge} = T_{sp} =$ | 298 | K |




For a quasi-steady state energy balance: $\mathbf{q_{in} = q_{out}}$

$q_{in}$ = Capacitance + Conduction to edges + Radiation to Space

$$q_{in} = (T_b^{i+1} - T_b^i) \times (mCp/dt) + (T_b - T_{edge}) \times (G_{12} + G_{13} + G_{14}) + \sigma FA\varepsilon \times ((T_b^i)^4 - (T_{sp})^4)$$

thus, $$T_b^{i+1} = T_b^i + (dt/mC_p) \times \{ q_{in} - (T_b - T_{edge}) \times (G_{12} + G_{13} + G_{14}) - \sigma FA\varepsilon \times ((T_b^i)^4 - (T_{sp})^4) \}$$

(This is valid if dt is less than thermal time constant for system)

Note: $T_b$ is the bulk temperature, not necessarily the peak for that area.